

Determination of Earth Orientation Using the Global Positioning System

A. P. Freedman

Tracking Systems and Applications Section

Modern spacecraft tracking and navigation require highly accurate Earth-orientation parameters. For near-real-time applications, errors in these quantities and their extrapolated values are a significant error source. A globally distributed network of high-precision receivers observing the full Global Positioning System (GPS) configuration of 18 or more satellites may be an efficient and economical method for the rapid determination of short-term variations in Earth orientation.

A covariance analysis utilizing the JPL Orbit Analysis and Simulation Software (OASIS) has been performed to evaluate the errors associated with GPS measurements of Earth orientation. These GPS measurements appear to be highly competitive with those from other techniques and can potentially yield frequent and reliable centimeter-level Earth-orientation information while simultaneously allowing the oversubscribed Deep Space Network (DSN) antennas to be used more for direct project support.

I. Introduction

Knowledge of the Earth's orientation in space is critical to the operation of NASA's Deep Space Network (DSN). Unless the orientation is closely monitored, the variable rotation of the Earth can lead to errors in spacecraft navigation. In near-real-time, high-precision spacecraft-tracking applications, the need for up-to-date Earth-orientation information is particularly crucial. The Magellan mission to Venus, for example, requires that Earth-rotation errors be kept under 30 cm;¹ by the mid-1990s, missions are envisioned that would require contin-

uously available Earth-orientation knowledge accurate to 3 cm.²

The Navstar Global Positioning System (GPS) is a network of orbiting radio transmitters designed for navigation purposes that is revolutionizing terrestrial distance determinations. The completion of the full satellite network by the early 1990s promises to extend recent improvements in regional geodetic measurements with GPS to a global scale [1, 2]. The capability of GPS to pinpoint receiver locations at the centimeter or subcentimeter level in a ter-

¹ T. F. Runge, "UTPM calibration accuracy for Magellan," JPL IOM 335.5-87.81 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 30, 1987.

² R. Treuhaft and L. Wood, "Revisions in the differential VLBI error budget and applications for navigation in future missions," JPL IOM 335.4-601 (internal document), Jet Propulsion Laboratory, Pasadena, California, December 31, 1986.

restrial reference frame that is precisely tied to an inertial frame suggests that GPS may be effective in monitoring Earth-orientation changes.

Earth orientation consists of three parts: the angle of rotation of the Earth about its rotation axis relative to a mean rotation angle (UT1-UTC), the position of the current axis of rotation of the Earth with respect to a reference axis tied to the crust and mantle of the solid Earth (polar motion), and the orientation of the rotation axis in inertial space (precession and nutation). The first two of these parameters, UT1 and polar motion, collectively known as UTPM (Fig. 1), vary as a result of angular momentum exchange between the solid parts of the Earth and its atmosphere, oceans, and fluid core. These Earth-orientation components can vary rapidly and unpredictably. Nutations and precession are primarily products of Earth's interactions with other celestial bodies and are largely periodic; they will not be dealt with in this article.

Earth orientation³ is currently being monitored by a number of precise geodetic techniques: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Lunar Laser Ranging (LLR). These techniques can currently achieve measurement accuracies of up to 2-3 cm over time scales as short as one hour [3]. The turnaround time necessary to collect and process these raw data can be quite long, however. VLBI from IRIS (International Radio Interferometric Surveying) provides daily UT1-UTC and five-day UTPM data, while SLR from CSR (Center for Space Research, University of Texas, Austin) provides three-day polar-motion data. The results, however, are not usually available until a week or more after the epoch at which the measurements are valid. This delay is not acceptable for many DSN navigation needs. VLBI data obtained by JPL using the DSN antennas are known as TEMPO (Time and Earth Motion Precision Observations) and can be processed rapidly when necessary; demands for radio-telescope time limit the frequency of observations to weekly, however. Prompt reduction of data can be critical to navigation since Earth orientation is continuously

changing. Earth rotation, in particular, is highly variable, and changes of 25 cm per day have been known to occur. Thus no system presently active is likely to meet the long-term DSN needs of regular, high-precision, daily monitoring of Earth orientation with data reduction times of less than one day.

VLBI, SLR, and LLR are, in addition, labor intensive and require significant investments in equipment and personnel. In VLBI, large radio telescopes are required—telescopes whose valuable observation time is in great demand at sites such as the DSN. The laser techniques use dedicated stations to obtain data but are subject to the vagaries of local weather conditions; thus they are not a reliable source for regular daily measurements.

If GPS technology could produce Earth-orientation measurements of a quality comparable to that produced by VLBI, SLR, and LLR, it would free up significant amounts of time on the DSN and other VLBI networks currently being used to monitor Earth orientation. It would, moreover, allow measurements to be made more frequently than is now practical with VLBI. In addition, the use of radio-frequency energy would enable GPS systems to be much less sensitive to weather than optical systems. GPS would not replace these VLBI, SLR, and LLR techniques (due to systematic difficulties described below); rather, GPS systems would be employed in a synergistic combination with these present-day techniques to enhance overall performance.

Frequent high-precision Earth-orientation data is also of value for scientific studies. Little is known about exchanges of angular momentum between the solid Earth and the atmosphere, or about the excitation of polar motions, at periods of a week or less. Continuous GPS monitoring would help to extend our knowledge to higher frequencies, with benefit to geophysics, meteorology, and astronomy. Weather forecasting, in particular, may benefit from independent estimates of daily atmospheric angular momentum as provided by geodetic Earth-orientation measurements.

A GPS receiver and data-processing system is scheduled to be in place at each of the DSN sites within a year to enable highly accurate, near-real-time ionospheric calibration in support of deep-space missions that transmit at a single frequency.⁴ This system is designed to have

³ Earth orientation is measured in a variety of units. Polar motion is essentially an angular displacement, while rotational variations can be expressed either as angular or temporal displacements. Both can also be expressed as a distance corresponding to the angular displacement measured at one Earth radius. Thus 1 cm at the Earth's surface is equivalent to an angular distance of approximately 0.3 marcsec or 1.6 nrad. The time it takes for the Earth to rotate through this angle and move a point at the equator to the east by 1 cm is approximately 0.02 msec of time. Thus 30 cm corresponds to 0.65 msec of Earth rotation or 9.6 marcsec (47 nrad) of polar motion.

⁴ C. J. Vegos, "DSCC Media Calibration Subsystem (DMD), Functional Design Review (Level D)," JPL 834-30, vol. 1 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1, 1987.

a data turnaround capability of about 12 hours. These receivers are also expected to be part of an international, global GPS tracking network for the TOPEX/POSEIDON mission [4]. By 1992, therefore, a GPS system should be in place to support the continuous monitoring of UTPM.

This article documents a covariance analysis evaluating the potential of GPS for measuring Earth orientation. The assumed satellite constellation is that originally proposed by the U.S. Department of Defense as the operational configuration. It consists of 18 satellites with 12-hour orbits and lying in six orbit planes equidistantly placed in longitude, three satellites per orbit plane. This constellation enables at least five satellites to be seen and tracked most of the time from anywhere on the Earth's surface [5]. Although the Air Force has subsequently modified this constellation to include up to 24 satellites, these changes should not significantly alter the conclusions of this study. The network of ground receivers is assumed to consist of six sites regularly spaced around the globe (three of these coincident with the DSN sites).

These sites are assumed to be equipped with receivers that yield two distinct observables: "carrier phase," based on measurements of the radio frequency (RF) carrier that is transmitted by the GPS satellites, and "pseudorange," based on a precise modulation of the transmitted signal. Both observables are indicators of the distance between a satellite and a receiver. Pseudorange consists of the light travel time between the two points, plus any clock offsets of the receiver and transmitter. It is often corrupted by multipath effects and is therefore the noisier data type. Carrier phase monitors the relative position change between the satellite and ground station. It is a cleaner data set, but the absolute distance is made ambiguous by a constant bias (equal to an integer number of wavelengths) for each continuously measured satellite arc.

Contemporary receiver capabilities are better for carrier phase than for pseudorange, but the quality of pseudorange data is rapidly improving. The GPS receiver being installed at the DSN sites can now achieve, under optimum conditions, pseudorange noise levels as low as 5 cm (averaged over 30 minutes), as well as carrier phase noise levels well below 0.5 cm [6]. By about 1992, when the full GPS constellation is active, such high-precision pseudorange and carrier phase data should be routinely available from numerous sites around the globe.

II. Covariance Analysis

This study utilized the Orbit Analysis and Simulation Software (OASIS) program, developed at JPL for the co-

variance and simulation analysis of Earth-orbiting satellites [7]. It consists of a number of independent modules: PV integrates the satellite orbits and computes the variational partial derivatives for satellite-related parameters; REGRES-PMOD generates simulated observations and their measurement partials; OAFILTER does the actual covariance analysis, i.e., using specified uncertainties of the data and the models, the program estimates the uncertainties in desired parameters; and UDIGEST generates the desired output. Parameters can be either estimated (adjusted) or "considered"; "considered" parameters are treated as systematic error sources [8]. Adjusted parameters can be modeled either as constants or as stochastic variables.

Parameters that can be adjusted include

- (1) satellite epoch states, i.e., their initial positions and velocities
- (2) various satellite force-model parameters such as solar-radiation pressure and Y-bias
- (3) satellite and station clock offsets
- (4) station locations
- (5) wet-zenith tropospheric path delay for each station
- (6) Earth-orientation parameters
- (7) gravitational harmonic coefficients and the value of GM (the gravitational constant, G, multiplied by the mass of the Earth, M)
- (8) geocenter offset
- (9) carrier phase biases

To determine Earth orientation with GPS, one needs to know the precise position and orientation of a set of points on the Earth's surface with respect to an inertial reference frame as a function of time. The GPS satellites provide an orbital reference frame that is not truly inertial but is slowly varying with time. Uncertainties in the GPS orbits can be reduced through estimation of parameters (1), (2), and (7) described above. The distances between satellites and receivers can be determined from the data after removing the effects of parameters (3), (4), (5), and (9). Determining the orientation of the satellite constellation in inertial space may be achieved by fixing the locations of a few ground receivers. These sites are known as fiducial sites and are tied by local ground surveys to nearby, colocated VLBI antennas whose relative positions in inertial space are known precisely [9]. The origin of this VLBI frame may not be coincident with the Earth's center

of mass as determined by the satellites; this geocenter offset (parameter 8) can also be estimated. Thus the satellite framework can be constrained in inertial space, and the movements of the solid Earth within that framework, such as Earth orientation, can be observed.

Appropriate a priori uncertainties for all estimated parameters are needed to strengthen the solution. Deciding which parameters to estimate or consider, what a priori values to use, and which data to include depends on the physical problem of interest.

The following questions were addressed in this study:

- (a) How many GPS measurements are necessary to generate Earth-orientation values with a precision comparable to present techniques? In other words, how long need the observation periods be in order to produce useful Earth-orientation data?
- (b) Are both pseudorange and carrier phase data types needed, and what maximum data noise is permissible for each type to allow adequate resolution of Earth-orientation parameters?
- (c) How important are the effects of solar-radiation pressure, station location errors, tropospheric uncertainties, and geocenter errors on Earth-orientation estimation? Do these parameters need to be estimated along with satellite states and Earth-orientation parameters, or can they be considered?

The parameter-estimation strategy is listed in Table 1. Earth-orientation parameters and their rates of change are all estimated with a priori uncertainties at least as large as the uncertainties expected in VLBI-provided UTPM prior to a GPS measurement, and at least a factor of 10 larger than the final, desired uncertainties. Satellite states and solar-radiation parameters are also estimated, with a priori sigmas comparable to the known uncertainties of the broadcast satellite ephemerides and of solar-radiation effects. Both DSN and non-DSN station locations are estimated, with the three DSN sites comprising the fiducial network constrained more tightly than the non-DSN sites. A priori sigmas for the station locations correspond to the present-day uncertainties of the VLBI baselines. The wet-zenith troposphere delay is estimated with an a priori sigma that is appropriate for a dry climate if surface meteorology data are available, and is more than adequate for wetter regions if water vapor radiometers are used.

The geocenter, carrier phase biases, and clock errors were all estimated with large, effectively unconstrained

a priori values. One station clock was fixed as a reference clock. All parameters were estimated as constants over the observing period, except for the clock errors, which were modeled as white noise [10].

The assumed data noise levels are appropriate for a DSN GPS receiver operating either in a poor, noisy propagation environment (20-cm pseudorange, 1-cm carrier phase) or in a reasonably good environment (5 cm, 0.5 cm, respectively). Note that these data noise levels assume individual measurements averaged over a 5-minute interval, or "batch."

Details of the software capabilities and modeling strategies for most parameters are described in [10]. Six matrix rotations⁵ are applied to station-location vectors to convert them from an Earth-fixed reference frame (1903.0 CIO frame) to a geocentric inertial system (J2000). Three of these rotations correspond to UT1 and the two components of polar motion. For this study, Earth-orientation rates are also needed. The UTPM components are thus modeled as $\theta(t) = a + b(t - t_0)$, where $\theta(t)$ is a UTPM parameter residual, a is the estimated value of the constant component at some epoch t_0 , and b is the estimate of the rate component.

III. Results and Discussion

Presented below are the results of covariance analyses for three distinct models summarized in Table 2. In model A, only pseudorange is employed, and these data have a high noise level. This model thus represents a "worst case" scenario for determining Earth orientation. Model B is identical to A, except that higher quality pseudorange data are assumed. Model C represents a near-optimal situation with regard to data quality: Both high-quality pseudorange (5 cm) and carrier phase (0.5 cm) are employed jointly. Note that this "best-case" model represents the expected quality of the data. In all of these models, station locations, wet-zenith tropospheric delays, solar pressure, clock offsets, geocenter offset, and carrier phase biases are assumed to be estimated along with Earth-orientation parameters and satellite epoch states.

The Earth-rotation parameter, UT1-UTC, is not expected to be directly measurable by GPS. An error in the satellite-node longitudes cannot unambiguously be sepa-

⁵ W. I. Bertiger, "Non-force models module," *OASIS Mathematical Description, V. 1.0*, JPL D-3139 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 1986.

rated from uncertainty in UT1. This is a problem common to all satellite geodesy, including SLR. If, however, GPS can determine the change over time of UT1-UTC, then this change can be combined with an initial value from VLBI measurements to yield the full UT1-UTC as a function of time.

Figure 2 illustrates the ability of GPS to monitor the rate of change of UT1-UTC, also known as length-of-day (LOD). With eight hours of observation, none of the models has achieved the measurement precision of present-day techniques. This present-day capability, available from VLBI or SLR after a processing delay of a week or longer, is indicated on Figs. 2, 4, and 5 by an arrow. With 16 hours of observation, however, model C, with its high-quality pseudorange and carrier phase data, can resolve LOD to better than 5 cm. By 24 hours, both models B and C show error levels comparable to or better than current uncertainties. The best scenario, model C, predicts subcentimeter LOD accuracy with 24 hours of GPS tracking.

This powerful ability to measure the rate of change of UT1-UTC enables the estimation of UT1-UTC with the help of VLBI. Because GPS and VLBI receivers are collocated at DSN sites, the VLBI and GPS reference frames should be precisely defined with respect to each other, yielding a high-quality GPS tie to inertial space. By integrating LOD over time, the total change in UT1-UTC can be estimated and added to an initial value determined from VLBI. If UT1-UTC can be measured accurately to 2 cm at an initial epoch, for example, daily estimates of LOD with GPS will add less than one centimeter per day to this uncertainty. To remain within 30 centimeters of the true UT1-UTC, VLBI measurements of UT1-UTC may only be needed monthly. This is illustrated in Fig. 3. Combining and smoothing all the data from various sources will yield better UT1 estimates, but these will only be available much later, after additional data are obtained. Thus GPS and VLBI are complementary techniques that can be combined synergistically to yield improved UT1 estimates.

Figure 4 illustrates the improvement with observing time of the Y component of polar motion (PMY). The X component (PMX) behaves in a similar manner and is not illustrated here. By 16 hours, the “best case” scenario of model C shows measurement accuracy comparable to present techniques, while by 24 hours model B (high-quality pseudorange) also yields an acceptable predicted error. The error estimates for all three models seem to be converging at the few-centimeter level. This is a limitation controlled mainly by the a priori station location uncertainties (constrained at 3–5 centimeters for each of three components).

Figure 5 shows the estimate of the error in the rate of change of PMY as a function of observing time; the rate of change of PMX error exhibits similar temporal variations. The behavior illustrated here is similar to that of the LOD component (Fig. 2). All three models show rapid improvement with time; by 24 hours, models B and C again achieve high-quality rate measurements. In the best case (model C), the error is down at the few-mm/day level.

It appears that GPS determination of Earth orientation is feasible for LOD, polar motion, and polar-motion rates. With less than 24 hours of tracking, these components will be as well-determined as measurements by current techniques. Recall, however, that current techniques only provide these values many days after the measurements are taken, whereas GPS is expected to deliver the results to the DSN within 12 hours. The best estimates come, as expected, with the smallest data noise. Combining high-quality pseudorange and carrier phase data reduces the uncertainties in Earth-orientation parameters most rapidly, achieving present-day measurement precision within approximately 16 hours. High-quality pseudorange data alone (model B) is the next-best option, measuring UTPM to an acceptable level within 24 hours.

Do Earth-orientation data continue to improve if observations are extended beyond 24 hours? And can UTPM be estimated every day with consistently high accuracy? To answer these questions, parameters that are not expected to change with time, such as station locations and GPS orbit epoch states, should be modeled as constant over the entire observing period. Earth-orientation parameters, which do change with time and for which one hopes to observe the most rapid variations possible, need to be periodically “reset,” i.e., their uncertainties inflated at regular intervals during the observing session while subsequent data attempt to constrain their then-current values.

Figure 6 illustrates this situation. Data are taken for 48 hours, with all parameters except Earth orientation and clock errors modeled as constant over this time period. Just after 24 hours, the uncertainties of the Earth-orientation parameters are reset at their a priori values (while clock errors continue to be modeled as white noise). Since additional data need only constrain Earth orientation, these parameters improve much more rapidly than in the first 24 hours. For comparison, Earth-orientation parameters estimated as constant over the entire 48 hours are also shown. This figure is produced with model B, using high-quality pseudorange only; performance is significantly enhanced if carrier phase data are included.

At 24 hours, PMY error is estimated to be 3 cm. Twelve hours after resetting (i.e., at 36 hours) the error is already down to 6 cm (versus > 10 cm in the first 12 hours); by 48 hours, the error is again at 3 cm. This compares with an error of 2 cm if PMY were estimated as constant over the full 48 hours. Although the 48-hour estimate after resetting is no better than the 24-hour estimate, the error drops much more rapidly in the second 24 hours than during the first. Thus polar-motion measurements every 12 to 16 hours may be possible with this technique, i.e., after other parameters have been suitably constrained during the first 24 hours.

UT1-UTC and PMY rates show even more pronounced improvement. LOD at 24 hours shows an error of about 2 cm; continuing to 48 hours brings this down to < 0.5 cm, while resetting at 24 hours yields 3 cm at 36 hours and 1 cm at 48 hours. The polar-motion rate improves from 5 cm/day at 24 hours to < 0.5 cm/day after 48 hours, and to < 1.5 cm/day if reset after 24 hours.

All these values are comparable to or better than present-day measurement capabilities whose time resolutions are 24 hours or more. Thus long arcs of GPS data show promise for frequent high-quality Earth-orientation measurements. Future studies will model Earth orientation stochastically, treating each UTPM parameter as a random walk whose standard deviation is allowed to grow in a manner consistent with the empirical behavior of UTPM.

To see whether station locations, solar-radiation pressure, geocenter location, and wet-zenith troposphere delay are all truly necessary to be adjusted along with satellite orbits and Earth orientation, a number of covariance runs were performed in which these parameters were considered. One of these is shown in Fig. 7. In this model, 20-cm pseudorange and 1-cm carrier phase were assumed. Solar pressure and geocenter position were adjusted along with satellite epoch states and Earth orientation, while station locations and wet-zenith troposphere delays were considered. All the Earth-orientation parameters and their rates show a high sensitivity to the considered parameters, as the formal error (labelled "Data") is dwarfed by the uncertainties due to considered effects. The station location errors, considered at 5 cm for each component, dominate the total error ("Total RSS sigma"), while the wet troposphere delay, considered at 1 cm, has a smaller but significant effect.

These results suggest that, with 24 hours of data, station locations and wet-zenith troposphere delays do need to be adjusted in the estimation in order to generate reliable UTPM estimates (as has, in fact, been done). Additional consider runs (not shown) demonstrate that solar pressure is a significant error source even at 12 hours and needs to be adjusted, whereas the geocenter location does not seem to have a significant effect on Earth orientation at an uncertainty level of 10 cm. Since consider errors scale linearly with the uncertainty in the considered parameter, if station locations are known to better than 1 cm in each component, their effects will not be significant at 24 hours. Similarly, it is not necessary to adjust the wet-zenith troposphere delay if it is known to better than 1 cm.

IV. Conclusions

This covariance analysis demonstrates that

- (1) High-quality length-of-day and polar-motion data can be obtained with GPS in under 24 hours, with a precision comparable to or greater than present-day techniques.
- (2) UT1-UTC may be reliably determined if periodic reference frame ties are performed, and initial values of UT1-UTC measured, with VLBI using colocated receivers.
- (3) The best combination of data types is high-quality pseudorange plus carrier phase, although high-quality pseudorange (data noise < 5 cm) alone performs well.
- (4) It is necessary at present to adjust solar-radiation pressure and Y-bias, station locations, and wet-zenith troposphere delay in addition to satellite states and Earth-orientation parameters. However, if the a priori uncertainties in the station positions or troposphere can be reduced, they need not be included in the estimation process.

In conclusion, it appears that GPS will be a useful addition to the collection of techniques currently employed to measure Earth orientation, and it may provide a reliable, economical method of monitoring in near-real-time high-frequency variations in UTPM. For the DSN, GPS methods may considerably reduce the demand for antenna time needed to measure Earth-orientation parameters while simultaneously enhancing the parameters' accuracy.

References

- [1] C. L. Thornton, J. L. Fanselow, and N. A. Renzetti, "GPS-based geodetic measurement systems," *Space Geodesy and Geodynamics*, A. J. Anderson and A. Cazenave, eds., London: Academic Press, pp. 197–218, 1986.
- [2] I. I. Mueller and S. Zerbini, eds., *Lecture Notes in Earth Sciences, Vol. 22: The Interdisciplinary Role of Space Geodesy*, (proceedings of an international workshop held in Erice, Sicily, July, 1988), Berlin: Springer-Verlag, 1989.
- [3] W. E. Carter and D. S. Robertson, "Project Polaris and IRIS: Monitoring polar motion and UT1 by very long baseline interferometry," *Space Geodesy and Geodynamics*, A. J. Anderson and A. Cazenave, eds., London: Academic Press, pp. 269–279, 1986.
- [4] R. E. Neilan and W. G. Melbourne, "GPS global tracking system in support of missions to the planet Earth," *CSTG Bulletin No. 11, New Satellite Missions for Solid Earth Studies—Status and Preparations*, C. Reigber (ed.), Munich, Federal Republic of Germany: Deutsches Geodätisches Forschungsinstitut (DGFI), for The Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), pp. 129–140, June 1989.
- [5] B. W. Parkinson and S. W. Gilbert, "NAVSTAR: Global Positioning System—ten years later," *Proc. IEEE*, vol. 71, no. 10, pp. 1177–1186, October 1983.
- [6] R. E. Neilan, T. H. Dixon, T. K. Meehan, W. G. Melbourne, J. A. Scheid, J. N. Kellogg, and J. L. Stowell, "Operational aspects of CASA UNO 1988—The first large-scale international GPS geodetic network," *IEEE Trans. Instr. Meas.*, vol. 38, no. 2, pp. 648–651, April 1989.
- [7] S. C. Wu and C. L. Thornton, "OASIS—A new GPS covariance and simulation analysis software system," *Proceedings First International Symposium on Precise Positioning with GPS-1985*, C. Goad (ed.), Rockville, Maryland, vol. 1, pp. 337–345, April 15–19, 1985.
- [8] G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, Orlando, Fla.: Academic Press, 1977.
- [9] J. M. Davidson et al., *The Spring 1985 high precision baseline test of the JPL GPS-based geodetic system: A final report*, JPL Publication 87-35, Jet Propulsion Laboratory, Pasadena, California, November 15, 1987.
- [10] S. M. Lichten and J. S. Border, "Strategies for high-precision Global Positioning System orbit determination," *J. Geophys. Res.*, vol. 92, no. B12, pp. 12751–12762, November 10, 1987.

Table 1. Parameter-estimation strategy (a priori sigmas)

Earth-orientation parameters	
UT1-UTC rate	10^{-7} (~ 10 msec/day)
PMX, PMY	80 nrad (~ 16 marcsec)
PMX, PMY rates	10^{-11} rad/sec (~ 200 marcsec/day)
Satellite parameters (18-satellite constellation)	
X, Y, Z positions	10 m (each component)
X, Y, Z velocities	1 mm/sec (each component)
Solar-radiation pressure (X, Z)*	50 percent
Y-Bias*	10^{-12} km/sec ² (100 percent)
Station parameters (6 stations with global distribution)	
DSN station locations*	3 cm (each component)
Non-DSN station locations*	5 cm (each component)
	(both 5 cm, if considered)
Wet-zenith troposphere delay*	10 cm
	(1 cm, if considered)
Other parameters	
Geocenter*	100 m (each component)
	(10 cm, if considered)
Carrier phase biases	10 km
Satellite and station clocks (modeled as white noise)	1 km (except one station)
Data noise	
Pseudorange	20 cm, 5 cm (5-min batches)
Carrier phase	1 cm, 0.5 cm (5-min batches)
* These parameters were considered in the covariance analyses discussed in the text, but are estimated in the models shown in Table 2.	

Table 2. Models

Model	Data
A ("worst case model")	20-cm pseudorange only
B	5-cm pseudorange only
C ("best case model")	5-cm pseudorange 0.5-cm carrier phase

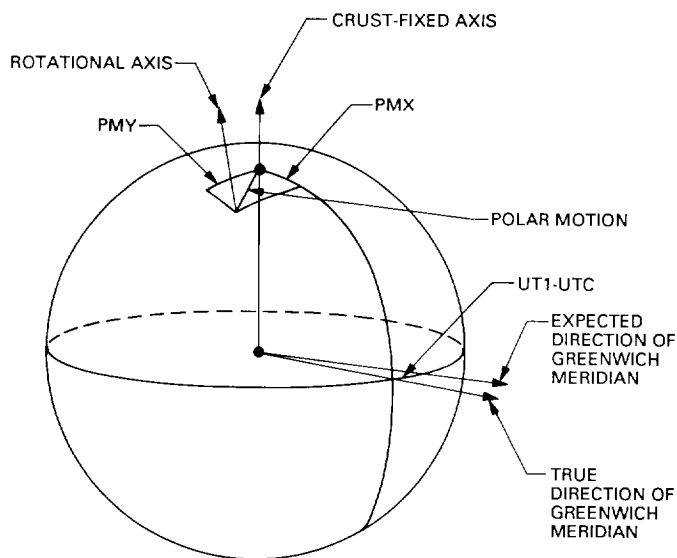


Fig. 1. Schematic illustration of the components of Earth orientation: polar motion (PMX, PMY) and UT1-UTC.

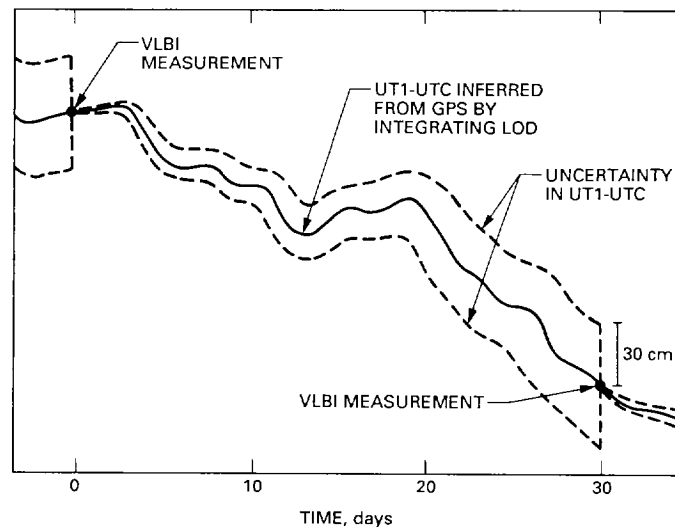


Fig. 3. Illustration of how precise periodic VLBI measurements of UT1-UTC can be combined with daily GPS LOD measurements to constrain the uncertainty in UT1-UTC.

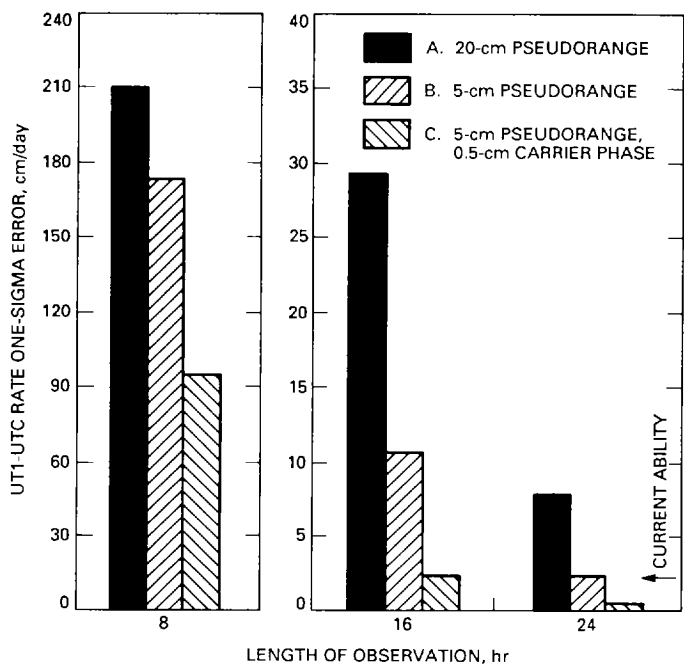


Fig. 2. Predicted uncertainty in the rate of change of UT1-UTC as a function of observation time. The arrow at right indicates present-day measurement capability in this and subsequent figures. Length-of-day uncertainty can also be found from this figure, as $LOD = (UT1-UTC \text{ rate}) \times 1 \text{ day}$. The units of LOD are cm.

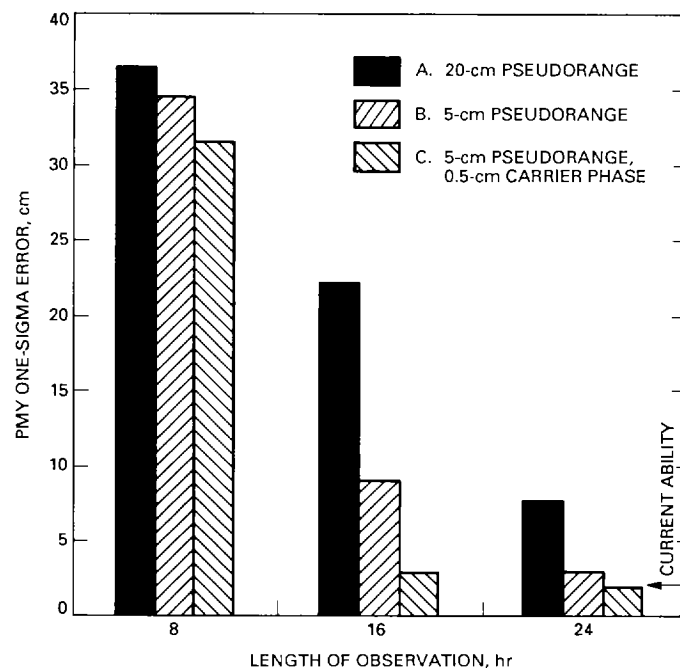


Fig. 4. Predicted uncertainty in Y polar motion (PMY) as a function of observing time. X polar motion (PMX) behaves in a similar manner.

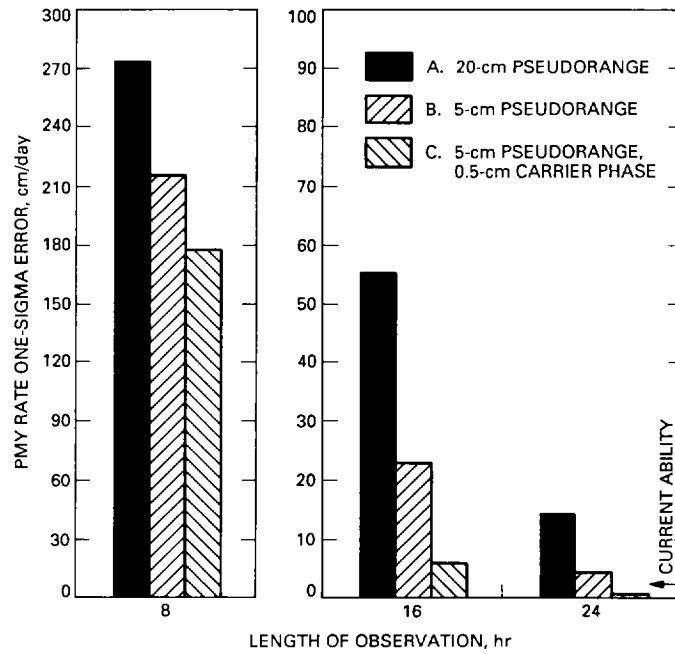


Fig. 5. Predicted uncertainty in the rate of change of Y polar motion as a function of observing time. The PMX rate behaves similarly.

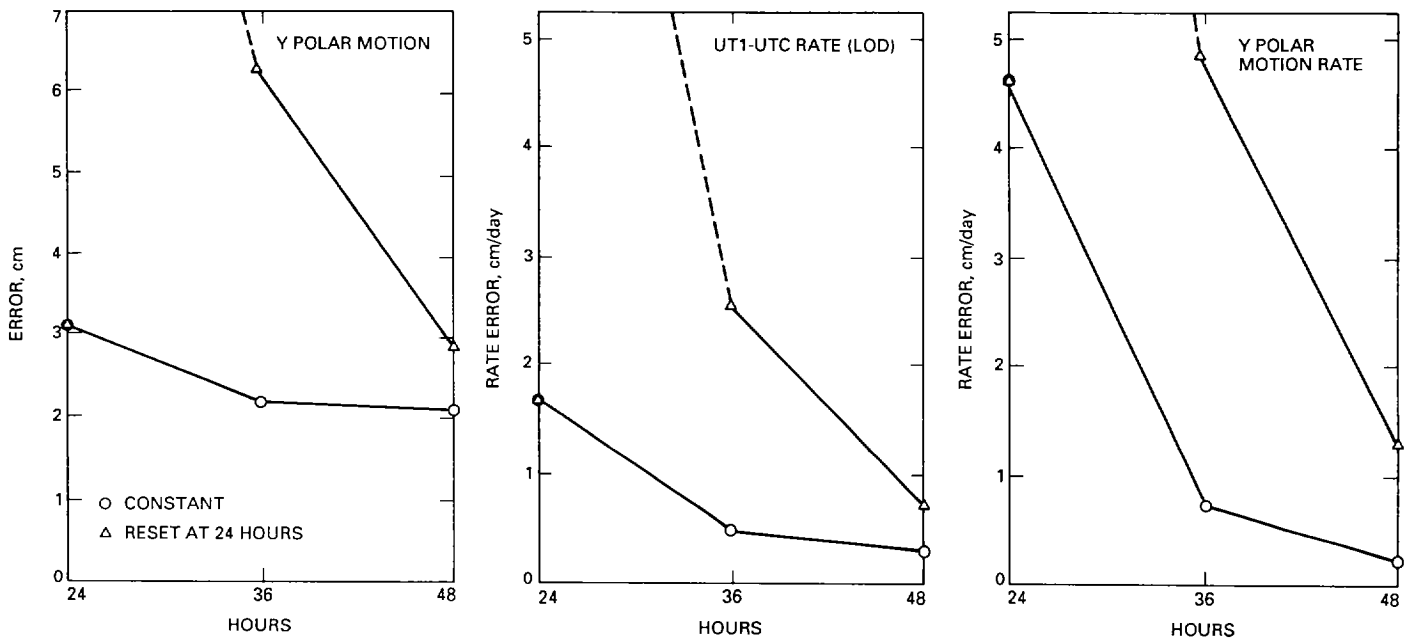


Fig. 6. Predicted improvement in estimates of UTPM after two days. Two cases are shown in which Earth-orientation parameters (○) are modeled as constant over 48 hours and in which these parameters (△) are reset to large values after 24 hours. Model B is used, employing only high-quality pseudorange data.

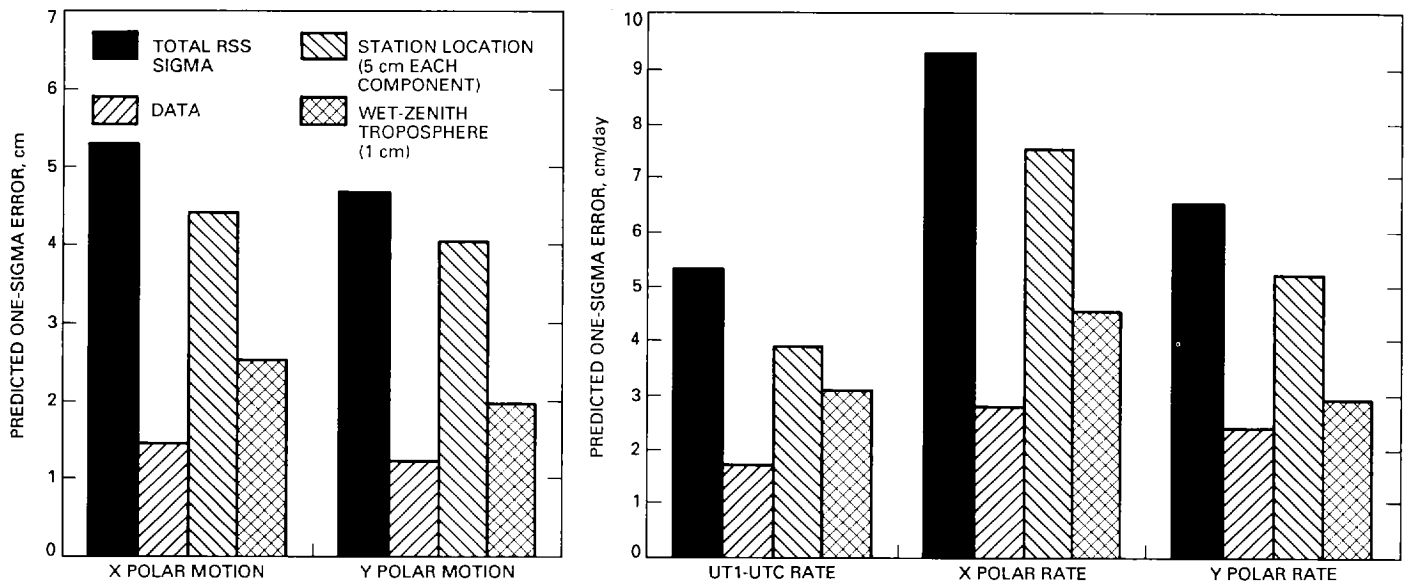


Fig. 7. Consider errors at 24 hours. Station locations and wet-zenith troposphere delay were considered with uncertainties of 5 cm per component and 1 cm, respectively. In this covariance analysis, satellite epoch states, Earth orientation, solar pressure, clocks, carrier phase biases, and the geocenter were all adjusted. The assumed data noise was 20 cm pseudorange and 1 cm carrier phase. The "Total RSS sigma" denotes the root sum square of the adjusted error estimate ("Data") and the two considered errors.